Final Report on AOARD contract FA4869-07-1-0045, "Laser cooling with ultrafast pulse trains"

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Overview.

The goal of this contract was to investigate a novel laser-cooling technique that uses femtosecond lasers to extend the range of ultracold atomic species. This contract continued the previous AOARD contract F49620-06-1-0313 of the same name.

Since the award of this contract on 6 April 2007, we have made significant advances toward a proof-of-principle laser cooling experiment in the ion trap and in construction of the apparatus for laser cooling of hydrogen. In the ion trap experiment, we

- compensated ion micromotion to optimize ion temperature and scattering rate
- characterized the stability of our novel UV frequency reference
- used automated high-speed laser pulse sequencing and data acquisition to measure ion scattering properties

With these advances, we now have the necessary degree of control over the trapped ions for a detailed study of femtosecond laser cooling in $^{174}Yb^{+}$. Currently we are attempting to drive the two-photon $S_{1/2} - D_{3/2}$ cooling transition using the high-repetition-rate femtosecond titanium:sapphire laser constructed for this purpose under our earlier AFOSR grant of the same name.

In the hydrogen experiment, we

- successfully operated the atomic hydrogen beam at room temperature
- constructed a supercontinuum light source for seeding the cooling laser system
- designed an efficient, robust nonlinear upconverter, a key part of the cooling laser

Construction of the hydrogen apparatus is proceeding steadily. Refurbishment of the atomic beam source is nearly complete. We have now published a paper on the dipole laser source constructed last year [PK08]. Seed light for the cooling laser system is now available from an all-fiber-based supercontinuum source that we have constructed from telecom fiber components. We have also designed an optimized upconversion system for generating >2 W of light at 243 nm starting from a thulium-doped fiber laser at 1944 nm.

Automation of ion-trap apparatus.

We have developed an automation system to control laser excitation and data acquisition in the ion trap experiment, a key requirement for ultrasensitive spectroscopy. The system

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14. ABSTRACT

Investigation of mode-locked laser cooling of atoms. Work supporting: 1) Demonstration of the principle of mode-locked laser cooling [Ki06] in a Yb+ ion trap, 2) Construction of the seed laser source for generating mode-locked cooling light on the 243 nm transition in hydrogen, and 3) Setting up a guided hydrogen atomic beam for mode-locked laser cooling of hydrogen. Plans were delayed by difficulties in finding qualified personnel and by component failures arising from the transport of the existing apparatus across the Pacific Ocean. Although the goals remain similar to those of 2006, significant progress toward goal 1 was achieved and the timeline for that goal has been revised accordingly in this current work plan.

15. SUBJECT TERMS
Atomic Physics, Femtosecond laser , Ultra Cooling

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consists of field-programmable gate array I/O hardware and LabView software, combining real-time control with straightforward and flexible programming. Thanks to the automation system, we are now able to apply repetitive sequences of laser pulses with approximately 2 μs timing resolution. Gated photon-count data can be collected with no dropouts at experiment repetition rates of at least 10 kHz. Since our data sampling rate of 40 MHz is considerably larger than the natural linewidth of the 369.5 nm transition, we have access to the full photon statistics of the ion fluorescence (see "Compensation of micromotion" below). We have used the automation system to measure the optical pumping time of the trapped ions under the 369 nm laser excitation. We find that the 1/e time to pump into the $D_{3/2}$ state is 7.5±0.7 μs when the 369 nm fluorescence rate is maximized. The $P_{1/2} \rightarrow D_{3/2}$ decay fraction has been measured to be 1/207 [YM00]. We infer a scattering rate of 8.9±0.8 MHz on the 369 nm transition, close to the theoretical maximum scattering rate of 10 MHz.

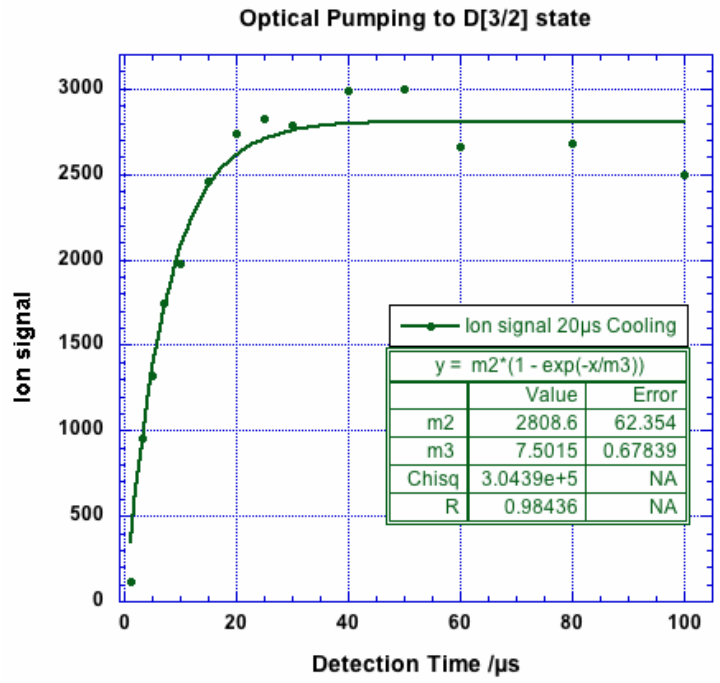

Fig. 1. Optical pumping time from $S_{1/2}$ to $D_{3/2}$ under 369.5 nm excitation of the $S_{1/2} - P_{1/2}$ cooling transition. The data is obtained from several thousand computer-controlled experimental repetitions of a laser pulse sequence with μs timing resolution, programmed using our automation system. The measured optical pumping time is 7.5±0.6 μs.

Demonstration of a novel optical frequency reference in the UV.

Our experiment uses standard single-frequency laser cooling to cool the ions to temperatures of a few mK. Our Doppler-sensitive detection of the two-photon femtosecond laser cooling transition will benefit substantially from use of a cold ion sample. We have constructed a novel atomic spectrometer for Yb^+ based on absorption

spectroscopy in a commercial hollow-cathode discharge lamp and used it to stabilize the cooling laser. We independently characterized the frequency noise of the locked laser by observing the fluorescence of the trapped ions. As shown in Fig. 2, the fractional frequency variation (Allan deviation) of the locked laser achieved a minimum of 2.5E-10 (equivalent to 370 kHz linewidth) for averaging time of 10-20 s. This work will shortly be submitted to Physical Review A.

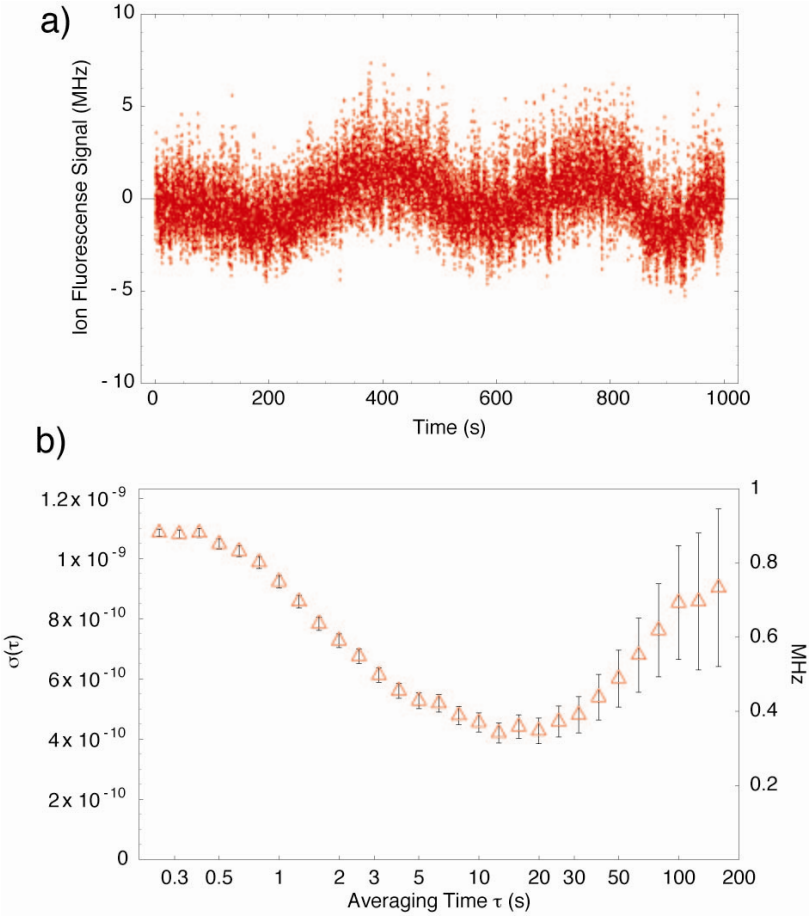

Fig. 2. a) Normalized ion fluorescence over 1000 s produced by the stabilized laser. b) Fractional frequency fluctuation (Allan variance) of the stabilized laser, as obtained from the ion signal. Error bars indicate 1σ confidence intervals.

This work is especially significant as being the first measurement of the stability of a simple ion-based frequency reference. As laser technology and laser cooling have pushed farther to the ultraviolet, a need has arisen for high-resolution frequency stabilization. In the near infrared, this need is met by spectroscopy of thermally-generated atomic and molecular vapors. The atomic and molecular species suitable for stabilization in the ultraviolet must be generated by more violent means, typically involving electrical discharges, and suffer from more severe line-broadening mechanisms that preclude the use of sub-Doppler spectroscopy. Our work demonstrates that these difficulties can be overcome, even in the most severe case of ions in a plasma.

Compensation of ion micromotion.

In radiofrequency (RF) ion traps like the one used here, the trapping potential is generated by the rapid reversal of an electric field gradient, i.e., an electric quadrupole potential. If the ions are pushed away from the trap minimum at $|E| = 0$, for instance by stray electric fields, the RF field induces motion of the ions at the RF frequency, Doppler-broadening the ion transition, inducing heating of the ions, and lowering the fluorescence rate. If appropriate diagnostics are available, this "micromotion" can be removed by applying compensating DC voltages to the trap electrodes.

We are now using the fluorescence cross-correlation method of Berkeland et al. [BW98] to diagnose and compensate ion micromotion in our trap. In this method, the arrival times of ion fluorescence photons are correlated with the RF trap drive voltage; when the ions sit at the trap minimum, the cross-correlation is minimized. Our automation system lets us avoid the expensive pulse-processing electronics normally used to implement the cross-correlation. Instead, the fluorescence photon arrival times are tagged by the automation system, and we extract the cross-correlation by postprocessing the arrival time data.

Hydrogen atomic beam apparatus.

Our atomic beam apparatus is based on a cryogenic hydrogen beam source donated by Prof. Daniel Kleppner, MIT, which was previously used for millimeter-wave spectroscopy of the Rydberg states of hydrogen. We are adapting the beam source to fit the rather different requirements of our laser cooling experiment. In particular, we have replaced the vibrationally noisy cryopump with a large diffusion pump for compatibility with the optical resonator. The acoustic noise from the cryopump was far too large to allow us to incorporate the high-finesse dipole trap resonator into the system. With the diffusion pump, there are no detectable vibrations in the vacuum chamber. We obtain base pressures below 1E-6 torr during operation under nominal gas load, a factor of 3 improvement over the base pressure obtained at MIT with the cryopump.

We have successfully operated the atomic hydrogen beam at room temperature. So far, the dissociation fraction is rather low: measuring the molecular beam composition with a residual gas analyzer shows that approximately 20% of the total flux is atomic hydrogen, the rest being H_2. During the use of the source by the Kleppner group at MIT, the dissociation fraction was typically higher than 70%. We attribute the poor dissociation to impurities at the surface of the RF dissociator tube, which will be eliminated by cleaning or replacement of the tube.

Seed light for the cooling laser system from an all-fiber supercontinuum source

We have constructed an all-fiber supercontinuum source in order to derive the 1944 nm light required for seeding the cooling laser system (Fig. 3). The supercontinuum source is constructed from commercially available, robust telecom components and operates stably without adjustment over a period of weeks. The source provides picosecond pulses of adjustable bandwidth and wavelength at 1944 nm. The power spectral density of the supercontinuum light at 1944 nm is 10 μW/nm, sufficient for seeding subsequent Tm-doped fiber amplifiers. Since the generated supercontinuum spans more than an octave (Fig. 4), we will be able to stabilize the absolute laser frequency using an f – 2f interferometer, opening the door to high-resolution frequency measurement of the 1S-2S transition.

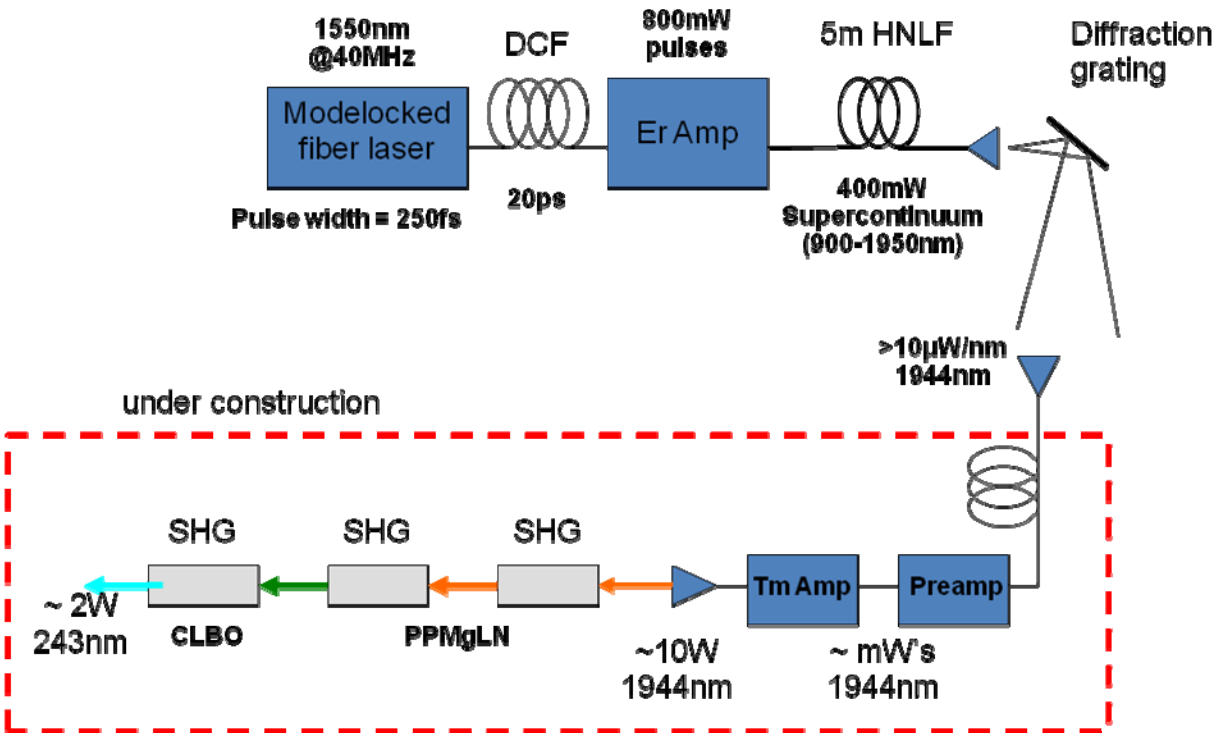

Fig. 3. Cooling laser system. The all-fiber supercontinuum source provides picosecond pulses of adjustable bandwidth at 1944 nm for seeding the cooling laser.

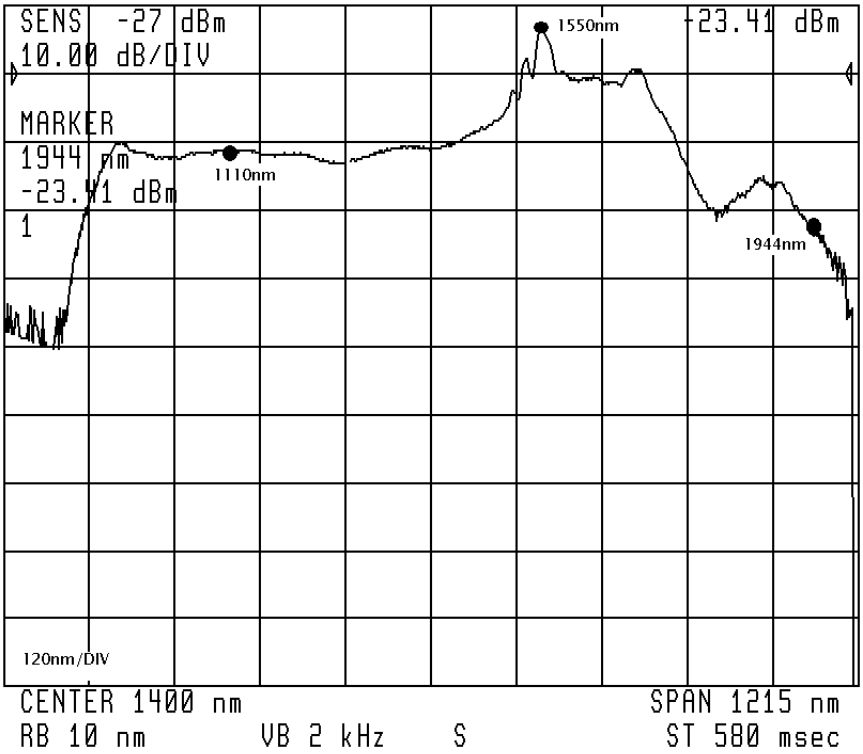

Fig. 4. Power spectrum of the octave-spanning supercontinuum source. The detector sensitivity of the spectrum analyzer decreases sharply at wavelengths above 1700 nm, causing an apparent drop in power. Power measurement with a photodiode gives a calibrated power spectral density of 10μW/nm at 1944 nm.

Upconverter design.

We have designed an efficient single-pass upconversion system for octupling our 1944 nm fundamental wavelength to the 243 nm wavelength required for laser cooling. The upconverter consists of three sequential second-harmonic generation (SHG) stages. For maximum nonlinearity, we will use periodically poled lithium niobate for the 1944 nm → 972 nm and 972 nm → 486 nm stages. As observed in our construction of the dipole laser system [PK08], we can avoid photorefractive damage to the upconverter by using magnesium-doped lithium niobate (PPMgLN). Because of the high UV absorption of poled materials, we will use a bulk crystal of cesium lithium borate (CLBO) for the 486 → 243 nm SHG step.

We have modeled the SHG processes in our upconverter system by 3D simulation of the nonlinear Maxwell equations by a split-step Fourier method, as implemented in the freely available software package SNLO [Sm03]. The efficiency, pulse distortion, and beam quality were optimized by adjusting the length of the crystal and the beam waist in the simulation. Table I gives the optimized results for an input 1944 nm beam of pulse energy 12 nJ and pulse duration 300 fs (i.e., average power of <10 W at repetition rate of

800 MHz, appropriate values for our system). Upconversion crystals for the optimized design have already been procured.

Step	**Material**	**Path length**	**Efficiency**	**M^2**	**Chirp**
1944 → 972	PPMgLN	3 mm	75%	1.04	10%
972 → 486	PPMgLN	0.5 mm	66%	1.03	6%
486 → 243	CLBO	5 mm	48%	1.15	16%
Total			**24%**	**< 1.2**	**< 30%**

Table I. Optimized design of high-efficiency upconverter for 1944 nm picosecond pulses.

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